Utilisation of GPS in large scale Photogrammetry

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0.Abstract

In the summer of 1987, a testflight was performed by the Survey De-
partment of Rijkswaterstaat in cooperation with KLM-Aerocarto, Techni-
cal University of Delft, Technical University of Stuttgart and Sercel
France. Objective of the test was to investigate the possible use of
airborne GPS navigation data during the photo-flight to reduce the
number of necessary ground control points. By incorporating the pha-
se-measurements of the GPS signal, an inner accuracy level for the ca-
mera positions of approximately 10 cm. was expected.
The photo-scale was 1:3700 with a forward lap of 70% and a sidelap of
60%. Extensive ground control was available, providing an independent
system for checking the GPS-observations. This paper discusses the re-
sults of the experiment mentioned in the above.

1.Introduction

In the photogrammetric mapping process, control points (points visible
on the photographs with known terrain coordinates) are used for the
transformation of the photo-coordinates to terrain-coordinates. The
geodetic measurements, necessary to determine the terrain-coordinates
of these control-points, are time-consuming and are an important
factor in the costs of the mapping process. For that reason
photogrammetric research has been focussed on a reduction of the
amount of ground control points.

This reduction is possible when the position (and orientation) of the
aerial camera is measured during the flight and introduced as an
observation in the photogrammetric block-adjustment. The extent of the
reduction is dependent on the accuracy of this observation. The
introduction of information about the altitude of the airplane as an
additional observation in the block-adjustment, is already a commonly
used method to reduce the amount of vertical control points for small
scale mapping projects.

The NAVSTAR Global Positioning System (GPS) has shown very accurate
results in both static and dynamic survey applications, especially
when using differential techniques. In a dynamic mode results with an
accuracy of a few metre are obtained by using psuedo-range code

measurements. Carrier phase measurements on the L1 or L2 frequency
have shown the potential to achieve the decimetre or centimetre level
of accuracy under dynamic conditions (refs 2,8 and 9).
If these results can also be reached when using GPS-techniques in an
airplane during a photogrammetric flight, GPS might become a powerfull
tool to measure the position of the aerial camera during the flight

A number of simulation studies have been performed recently to
investigate the required accuracy of this position information as a
function of a.o. the photo-scale of the project (refs 1 and 2). These
simulations indicate, that for a photogrammetric block, the number of
control points can be reduced to only four points in the corners of
the block if the camera positions can be determined with an accuracy
of 4 metres for small scale mapping (photo-scale 1:50.000). For large
scale mapping (photo-scale 1:4000), an accuracy of 15 centimetres is
required.
Depending on the computational techniques that are used, GPS might
cope with the demands from both small and large scale photogrammetric
applications.

The Survey Department of Rijkswaterstaat is (among other tasks),
responsible for the revision and production of maps from the national
highways, the main rivers and the Dutch coast. Around 90% of the
mapping is done by photogrammetry, at photo-scales 1:5000. The mapping
process at the Survey Department will be changed from analoque to
digital during the next years, resulting in a topographical database
as a product in stead of maps. This conversion will cause an increase
in the amount of photogrammetric projects for the next years, which
means that any substantial reduction in the necessary ground control
will make substantial savings.

In order to test the capabilities of differential GPS under practical
conditions for large scale mapping purposes a research project has
been realised by the Survey Department in cooperation with
KLM-Aerocarto ,Sercel and the Technical Universities of Delft and
Stuttgart (W-Germany). The research aspects are twofold:
        -to establish the attainable accuracy for an airborne
         dynamic GPS-positioning system.
        -to establish the attainable reduction of ground control by
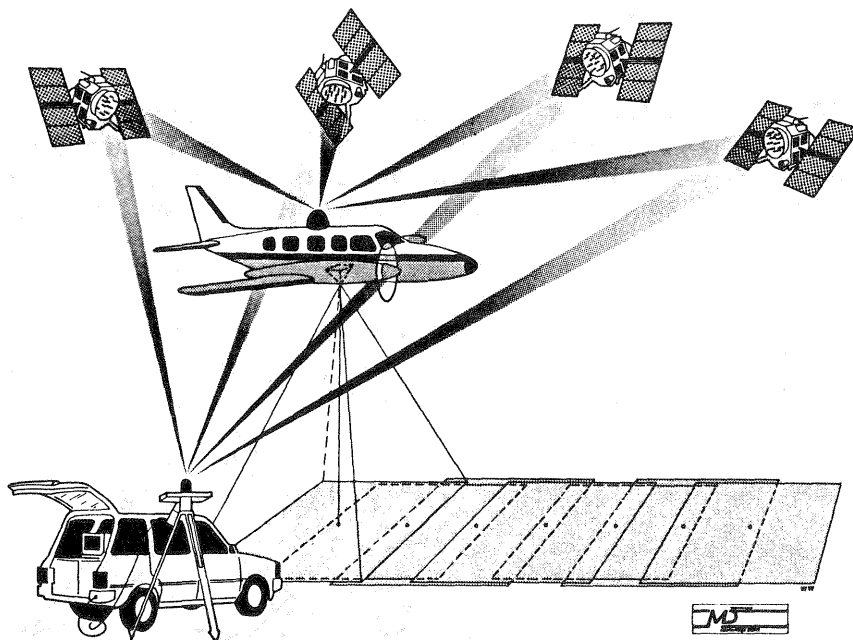   introducing GPS camera positions in a photogrammetric
         block adjustment
The focus of this paper is mainly on the first part of the pro-
ject. From the evaluation of the second part, the introduction
of the GPS positions in the block-adjustment, only preliminary
results are shown. A further evaluation of the data is still in
progress.

2.Test setup

The attainable accuracy for GPS during a photogrammetric flight
is analysed by comparing the projection-centre coordinates
computed from GPS observations during the flight with the
coordinates resulting from a photogrammetric block-adjustment.

The test setup is shown in figure 1.

Differential GPS : an efficient tool in Photogrammetry

figuur 1 : the test setup

An airplane was adapted to accomodate a Sercel GPS receiver
(type TR5SB) and an antenna. The antenna was mounted as close to
the camera as possible, and its position with respect to the
photo-system, and thus relative to the projection centre of the
camera was accurately measured. A second GPS-receiver (Sercel
type NR52) was placed at a known reference point on the ground.
This receiver is used as the differential station. The receivers
are capable of performing both C/A-code pseudorange measurements
and L1-carrier phase measurements to five satellites simulta-
neously.
The antenna coordinates during the flight can be computed from
the GPS observations and converted to projection-centre coor-
dinates.

The photogrammetric projection-centre coordinates, which are the
reference coordinates for the GPS results should have an accura-
cy of 10 cm or better. That level of accuracy can only be reali-
sed from a photogrammetric-flight over a testfield with exten-
sive targetted and accurately surveyed ground-control. Beside
that the photogrammetric block should be strong, meaning large
forward lap between the photographs in a strip, and large
sidelap between the adjacent strips.

The projection-centre coordinates resulting from the photogram-
metry are the coordinates at the exact time of exposure of the
photographs. In order to determine the GPS-coordinates at that

same time, a hardware connection between the camera and the GPS-receiver should be realised.
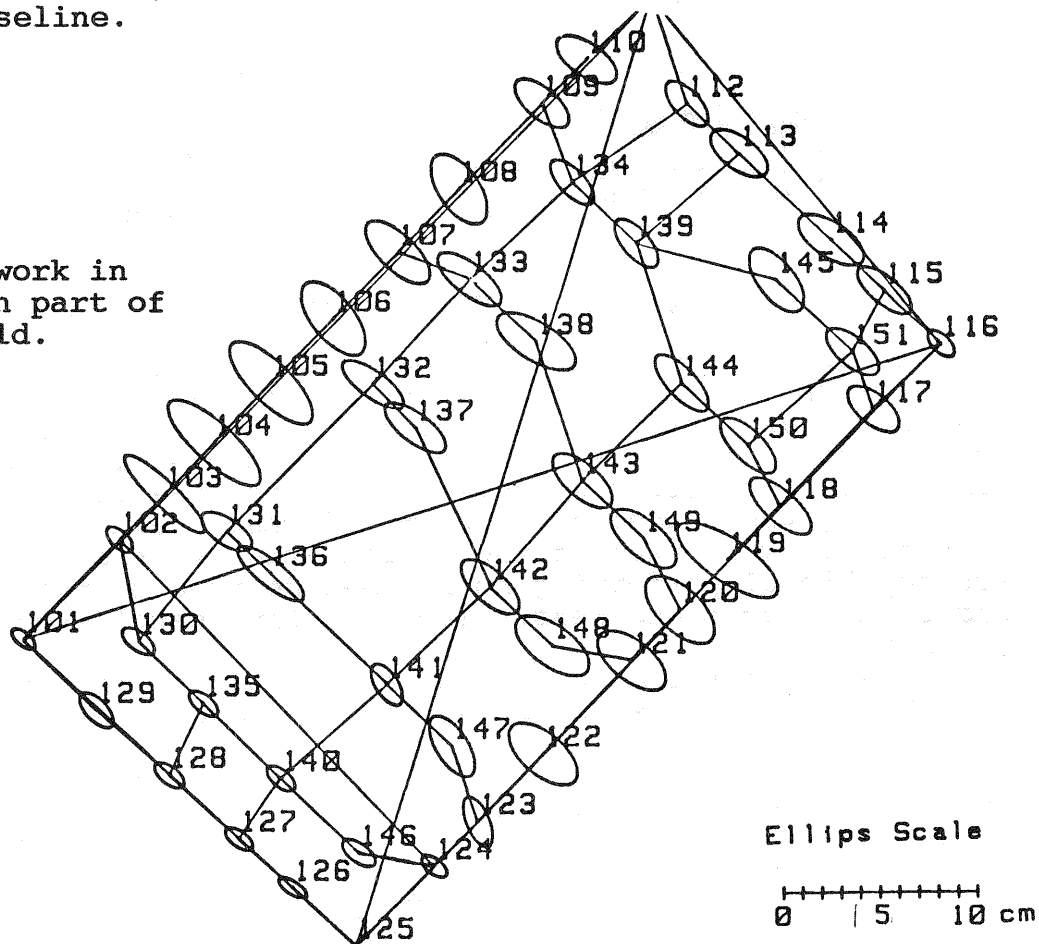

3.Realisation of the test
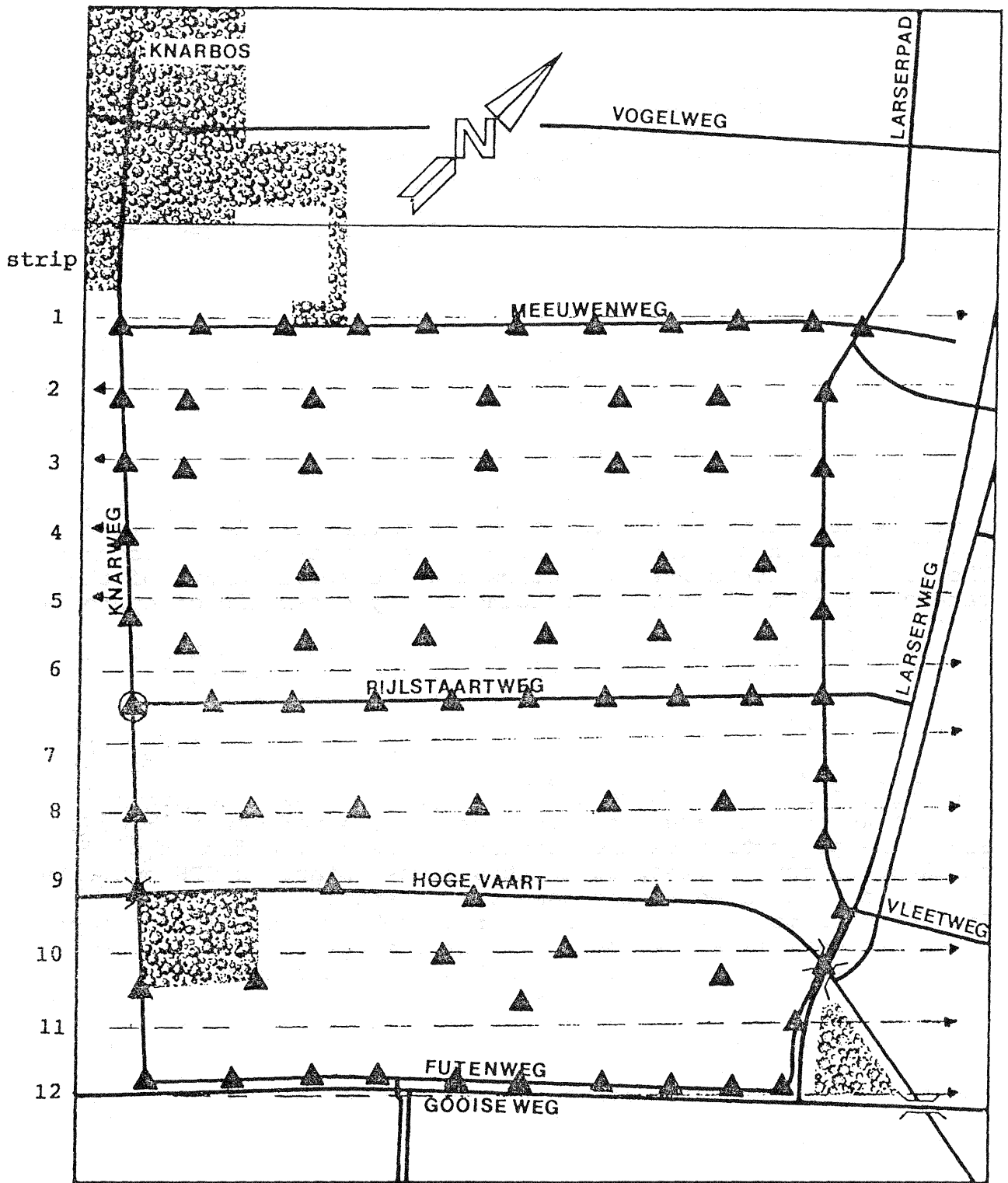
<u>the testfield</u>
For the project, a special testfield has been created covering an area of approximately 4*4 kilometres. A total number of 80 ground control points were painted on the roads in a regular grid with mutual distances of 400 metres as shown in figure 2.

All 80 points were surveyed with conventional geodetic methods. The Northern part of the testnet covering 50 points was also surveyed with two Trimble 4000S GPS-receivers. With these receivers, a network with 75 baselines (figure 3) was completed in three weeks time, with a mean observation time of 30 minutes for each baseline.

figure 3:
the GPS network in
the Northern part of
the testfield.

The raw GPS data has been processed with the Trimble software-package TRIM-640H, using the double difference integer fix solution. The resulting baseline-components and their corresponding covariance-matrices are input in a free network adjustment program, in order to obtain one consistent set of coordinates for all 50 control-points. In this adjustment program, which runs on a HP micro-computer, a testing and data-snooping

figure 2: the testfield

procedure has been implemented to detect gross-errors in the measurements.
Based on the results of the adjustment, the overall internal coordinate precision for the ground control points can be estimated from the a-posteriori covariance matrix. This precision proved to be 2-3 centimetres (1 sigma).
The coordinates of all points are computed relative to one base-point and transformed to coordinates in the Dutch national reference system and ellipsoidal heights above the Bessel-ellipsoid. The coordinates for the base-point are determined from the best C/A code solution.

the test flight
An airplane from KLM-Aerocarto and two GPS-receivers were available for the test during a period of two weeks in june 1987. Due to bad weather conditions only two flights could be realised during this period, the first one on june 10th, the second one on june 12th. Both flights were interrupted prematurely due to lowering clouds and turbulence.
The complete flights resulted in 16 parallel strips with a forward lap of 70% and a sidelap of 50%, which means that approximately 360 photographs were taken from the testfield (figure 2). The photographs are taken with a time-interval of 3 seconds. The flight altitude was 770 metres and the focal length of the camera 213.67 millimetre, resulting in a photo-scale of approximately 1:3700.
The strips were flown in two opposite directions (SW-NE) and (NE-SW) to be able to trace possible sytematic effects in the results, which are a function of the flight direction (e.g timing errors).

the configuration in the airplane
The exact time of exposure of a photograph is defined as the time at which the camera-shutter reaches its maximum aperture. Since the projection-centre coordinates resulting from the block-adjustment correspond to this time-instant, a GPS position has to be calculated at the same time-instant.
In fact this means that there are two problems to solve namely:
 -how to determine the moment of maximum aperture of the camera
 -how to relate this moment with the GPS measurements
With the Sercel receiver a pulse, coming from an external device can be timed in the receiver-timeframe with an accuracy better then 1 millisecond. The pulse is thus timed in the same timeframe as the raw satellite data and related to GPS-time. The position at that time-instant can be computed by interpolation. This possibility is used to relate the GPS measurements to the exposure time-instant.

With the Wild RC 10 aerial camera, used for this test, an external pulse can be generated, which is related to the moment at which the shutter is released. However the time-interval between the maximum aperture and the release of the shutter proved to be variable at the 10-100 millisecond level. With a ground speed of 100 m/s this would cause errors in the order of 1-10 metres.

To overcome this problem, a special light-sensitive device was placed inside the camera, generating a pulse when the shutter reaches its maximum aperture.With this device a timing accuracy better than 1 millisecond is achieved.

During the flight raw GPS-data (C/A-code and carrier-phase data) is recorded simultaneously in the airplane and at the differential point every 0.6 seconds. A real-time solution from the airborne GPS-receiver is used for on-line quality control in the airplane.

4.Data processing

The GPS observations

With the GPS-system we can distinguish between two different observables, the pseudo-range code observable and the carrier phase-observable. An instantaneous position can be computed from the pseudo-range measurements to four satellites. For a single point solution the precision will be rather poor (10-20 metres) but for a differential solution it will be far better (2-3 metres). With the (integrated) carrier-phase observable only relative positions can be computed since the initial number of cycles (the initial pseudo-ranges to the satellites) are unknown. These relative positions can be computed with a very high precision, especially in a differential mode the centimetre level is obtainable. From the accuracy requirements for large scale photogrammetry it is clear that the computations should be based on the use of the carrier-phase observable.

There are two options to overcome the problem of the cycle ambiquities for differential kinematic positioning. The first option is to start at a known position with both the differential and moving antenna (or with both antennas on the same point). The second approach is to try to obtain an estimate for the initial cycle ambiguities at both receivers, by averaging the differences between the measured pseudo-ranges and the integrated phase observables over a certain period of time. This last approach (ref 5) is based on the assumption that at each epoch i the difference between the pseudo-range measurement $P(i)$ and the integrated phase measurement $D(i)$ is a constant but arbitrary value A. As soon as this value is computed from n measurements $P(i)$ and $D(i)$ at n different epochs, a smoothed pseudorange __P(i)__ can be computed for every next epoch from:

$$\underline{P(i)} = A + D(i)$$

The precision of this smoothed pseudo-range is determined by the precision of the phase-observable (mm-level) and the precision of the estimate for the value A.
In the real-time kinematic software developped at the Survey Department, the smoothed pseudo-range at epoch i is computed from:

$$\underline{P(i)} = \frac{(i-1)*(\underline{P(i-1)} + D(i,i-1)) + P(i)}{i}$$

which can be written as:

$$\underline{P(i)} = 1/i*(\quad(P(n)-D(n))) + D(i)$$

In the first part of this formula, the best estimate for A at epoch i is thus computed from a moving average. With the assumption that the observations are not correlated, the precision improves with every next epoch. It will be obvious that the noise level of the first position fixes is mainly determined by the noise level of the pseudo-range observations. To obtain the same high precision for all position fixes, the data is recomputed in a post-processing mode based on the best estimate for the value A and the phase observable D(i) at every epoch.
This computational technique is used for both the stationary and the moving antenna. The differential corrections for the moving antenna are computed from the known position of the stationary point and the computed position at every epoch i.

The photogrammetric processing
For the photogrammetric processing, two different aerial triangulation methods are used. At the University of Stuttgart the projection-centre coordinates are computed with the bundle adjustment program PAT-B, at the Survey Department of Rijkswaterstaat with an independent model adjustment program FOTEF. Only a part of the aerial-triangulation of all 360 photographs has been completed so far.
From the independent model adjustment, the results of a block formed by four strips from the flight on june 10th (stripno. 3,4,5 and 6 in figure 2) are available for the further analysis. The 70 projection-centre coordinates resulting from this adjustment are transformed to antenna-coordinates. For this transformation the position of the antenna relative to the projection centre and the orientation of the camera must be known. The position of the antenna is measured before the flight in the camera system (dx=3cm, dy=-7cm, dz=146cm). The three orientation elements for every photograph are obtained as a result of the block-adjustment. Since the variations in these orientation elements proved to be very small within one strip, these parameters are computed from the first photograph in each strip and used for all other photographs within that strip.
From the bundle adjustment, the results of a block formed by seven strips from two different days (strip 2,3,4 and 5 on june 10th and strip 7,6 and 1 on june 12th) are used for the further analysis. This block provides us with 121 projection-centre coordinates as a reference for the GPS antenna coordinates. These projection-centres are only corrected for the vertical offset between the antenna and projection-centre, neglecting the tilt of the camera.

<u>Introduction of the GPS positions in the independent model adjustment</u>

At the Survey Department the program FOTEF is normally used for the triangulations. FOTEF was designed with emphasis on speed and small memory requirements; this made the program difficult to modify.

In independent model triangulation, the projection-centres are measured and used as tie-points between models. Thus, they appear both as observations and as unknowns in the adjustment equations.

$$dx^m + v^m = A^m dx^T + B\ dx^e \qquad (1.1)$$
$$dx^t + v^t = I\ dx^T \qquad (1.2)$$

with x^m and x^t observations in the model system resp. the terrain system, X^T and X^e the unknown terrain coordinates resp. the unknown model orientation parameters. v^m and v^t being the corrections to the observations.

Yhe simplest to introduce the GPS observations would be to expand the equations for every projection-centre as follows:

$$dx^m_{pc} + v^m_{pc} = A^m dx^T_{pc} + B\ dx^e \qquad (2.1)$$
$$dx^{pc}_{pc} + v^{pc}_{pc} = I\ dx^T_{pc} \qquad (2.2)$$

In fact, these are the same type of equations that are used for ordinary ground control points. This approach treats the GPS coordinates as absolute observations.

An other approach is to introduce the projection-centres in the adjustment as being observed in a seperate model, overlapping all the "real" models forming the block; thus modelling possible systematic effects in the GPS observations.

$$dx^m_{pc} + v^m_{pc} = A^m dx^T_{pc} + B^m dx^{e,m} \qquad (3.1)$$
$$dx^{pc}_{pc} + v^{pc}_{pc} = A^{pc} dx^T_{pc} + B^{pc} dx^{e,GPS} \qquad (3.2)$$

with A^{GPS}, B^{GPS} and $dX^{e,GPS}$ being the design matrices resp. the orientation parameters for the "super" model containing all GPS observations. This implies that seven additional unknowns are introduced and some groun control is needed to establish the absolute orientation of the block.

If the results of the triangulation must refer to the national datum, at least three points must be known in both WGS84 and the national datum.

Both approaches, flight control and "super" model were introduced in FOTEF. The implementation of the "super" model required so many patches to the original program, that no reliable results could be obtained until now.

5.Data analysis

<u>GPS position accuracy</u>

The interpolated antenna positions computed from the differential GPS observations are directly compared with the photogrammetric results.

First the differences between GPS and the photogrammetric independent model adjustment are analysed. For each strip the mean coordinate difference in the three components (dX,dY and dh), the corresponding standard-deviations (SX,SY,Sh) and the observation period are listed in table 1.

june10th	dX(m)	dY(m)	dh(m)	SX(m)	SY(m)	Sh(m)	period
strip 3	-.285	.184	.849	.199	.245	.064	11:08-11:09
strip 4	.144	-.247	.719	.111	.136	.106	11:19-11:20
strip 5	-.088	-.026	.630	.208	.263	.115	11:28-11:29
strip 6	.193	-.006	1.176	.203	.133	.061	11:23-11:24
all strips	.009	-.024	.884	.180	.194	.087	21 minutes

table 1: mean antenna coordinate differences for each strip
(Independent model adjustment - GPS)
with their corresponding standard deviations

The maximum coordinate difference in the horizontal components
is less then 30 cm with a standard deviation between 20 and 30
cm. In the vertical component however larger differences are
found, with a mean coordinate difference of 1.17 metre for strip
6 as a maximum. As for the cause of the different results for
the horizontal and vertical components further analysis of the
data is in progress. In spite of this coordinate difference, the
standard deviations in the vertical components within each strip
are between 6 and 11 cm, so well below the values found for the
horizontal components.
The mean coordinate differences in the vertical components show
a drift of -0.15 mm/second for the strips 3,4 and 5. The results
from strip 6 however do not confirm this drift.

In the block-adjustment program, an estimate for the precision
of the photogrammetric reference coordinates is computed from
the a-posteriori covariance matrix. The resulting standard-
deviations for the horizontal and vertical components are 10 and
6 cm respectively. When these values are taken into account,the
estimated standard-deviation for the GPS-positions is 15 cm for
the horizontal and 7 cm for the vertical components

In table 2 the results from a comparison of the GPS antenna
coordinates with the antenna coordinates from the bundle
adjustment are listed. The table shows the mean coordinate
differences in all three components (dX,dY,dh), the correspon-
ding standard-deviations (SX,SY,Sh) and the observation period.

june10th	dX(m)	dY(m)	dh(m)	SX(m)	SY(m)	Sh(m)	period
strip 2	-.122	.055	.776	.075	.061	.039	11:02-11:03
strip 3	-.041	-.032	.727	.065	.058	.039	11:08-11:09
strip 4	-.010	-.011	.624	.062	.062	.033	11:19-11:20
strip 5	.020	-.018	.512	.059	.059	.047	11:28-11:29
june12th							
strip 7	.133	.157	.973	.094	.095	.046	11:33-11:34
strip 6	.163	.032	1.140	.060	.075	.047	11:40-11:41
strip 1	.238	-.099	1.355	.058	.085	.050	11:46-11:47
all strips	.054	.012	.903	.067	.070	.043	41 minutes

table 2: mean coordinate differences for each strip
(Bundle adjustment - GPS) and the correspon-
ding standard deviations.

remark: only corrected for vertical camera/antenna offset

For the four strips flown on june 10th the mean difference in
the horizontal components varies between 3 and 12 cm and for the
three strips on june 12th between 16 and 26 cm.
The standard deviations in the horizontal components are well
below 10 cm. for both days. The vertical components show even
better results with standard deviations below 5 cm.
Again the coordinate differences in the vertical components are
quite large. The drift in these components, -0.16mm /second, is
almost identical to the one computed from the results in table
1. For june 12th this drift is 0.45 mm/second.

The precision of the photogrammetric reference coordinates
computed with the bundle adjustment are estimated from a
simulation studie; a standard-deviation of 4 cm. for the hori-
zontal and 2 cm. for the vertical components is found.
If one considers the contribution of these values to the results
listed in table 2, the precision for the GPS-positions based on
the results of all seven strips is 5 cm for the horizontal and 4
cm for the vertical component.
These results are 2-3 times better then those obtained in the
comparison with the independent model adjustment, in fact they
are better then the estimated precision of the reference coordi-
nates from the independent model adjustment.

In figure 5 (on the next page) the coordinate differences for all positions are plotted seperately for the x-, y-, and height-component. Only for the height component there is a change in the coordinate differences between strip 5 and 7, so between the results from the two different days.

To analyse systematic effects in the horizontal components in more detail, figure 6 shows a vector plot of the coordinate differences for all 121 positions.
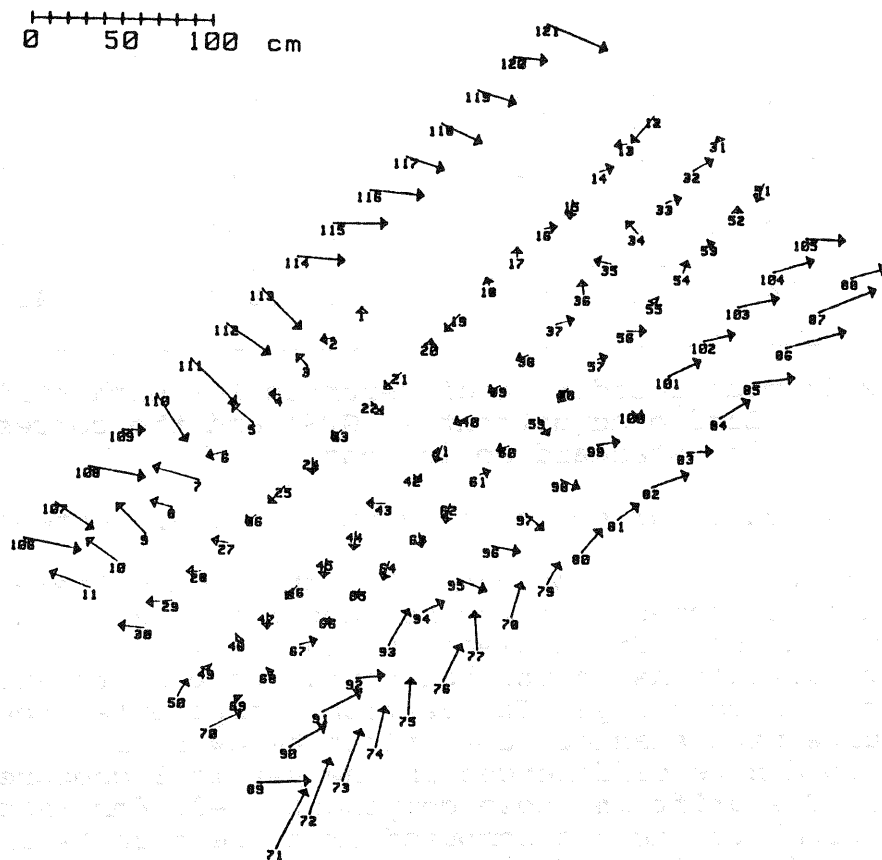

figure 6: vectorplot of the horizontal coordinate
         differences

The numbers in the plot correspond to the consecutive photographs.
For the first 70 positions, the results of june10th, no systematic effects are visible. The results from june 12th however show a clear systematic effect. For the first position, point 71, the vector is oriented N-E and its length is 25 centimetres. Throughout the three strips, the orientation of the vector changes from N-E to S-E, whereas its length varies between 16 and 26 cm.
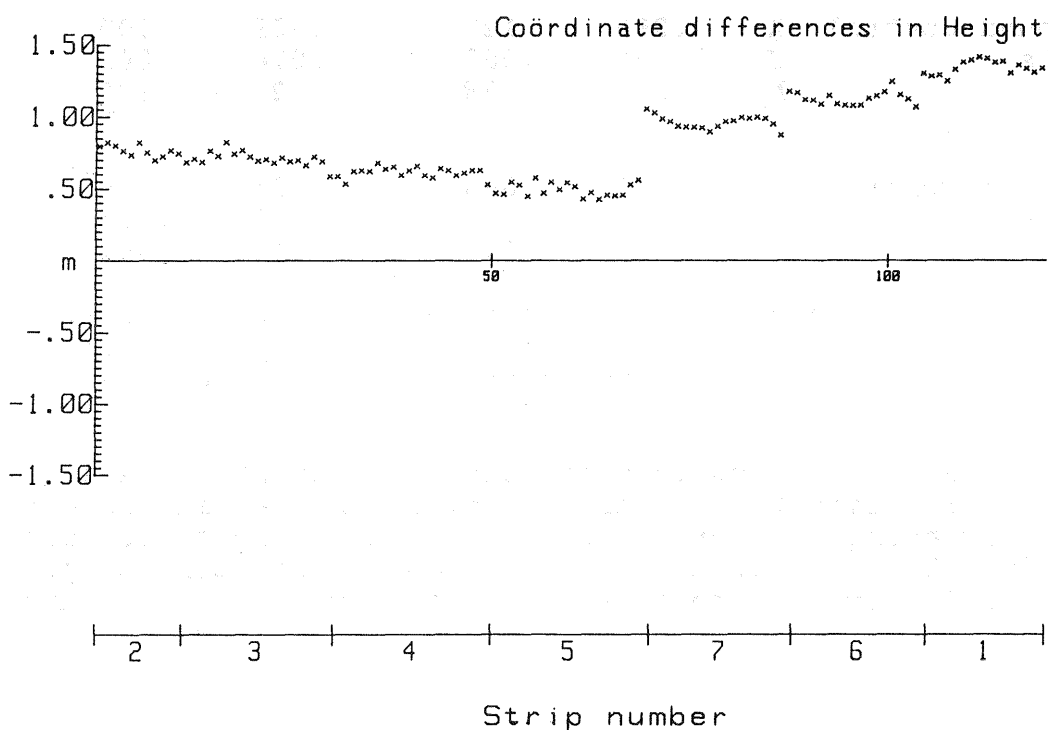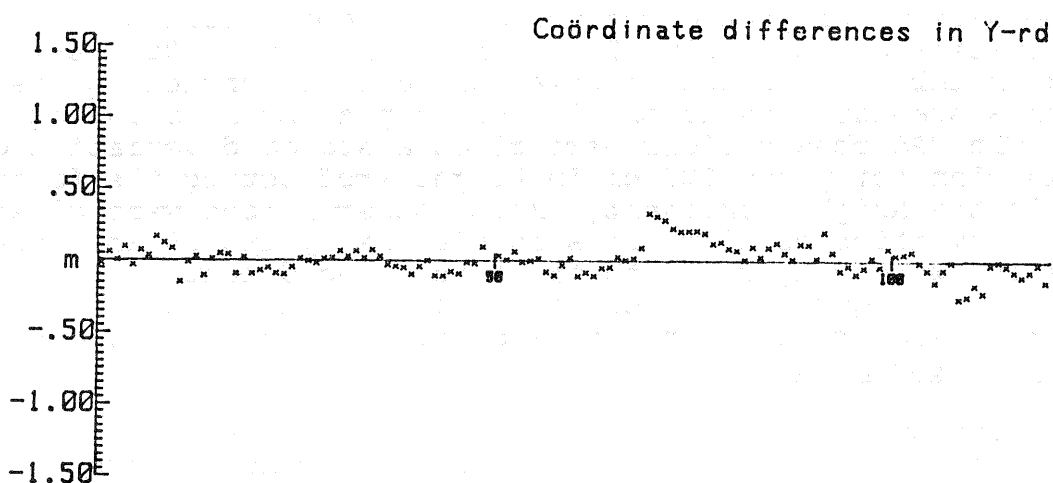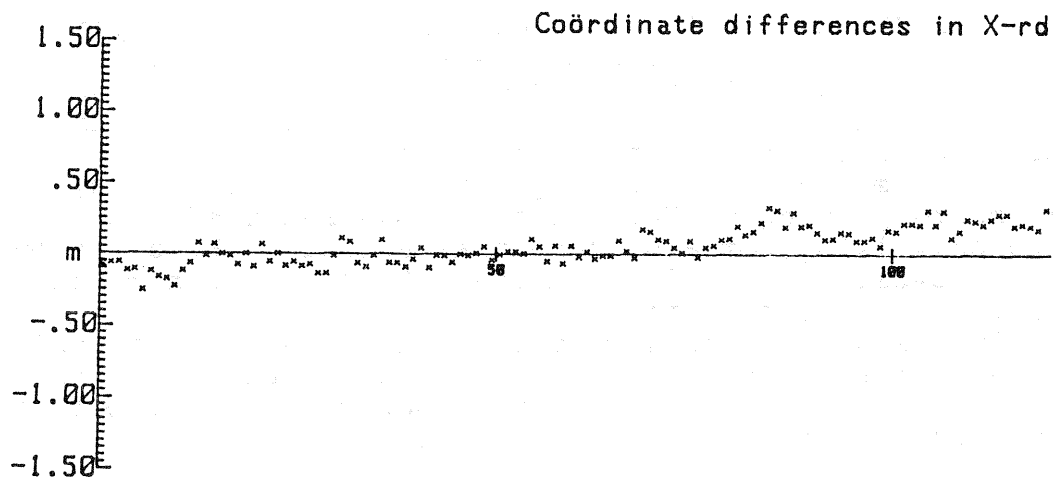Both coordinate difference and systematic effect are probably

figure 5: coordinate differences between GPS and
photgrammetry (bundel adjustment)

caused by the GPS processing approach. As discussed in par.4,
estimates for the cycle ambiguities A are computed from the
averaged differences between the pseudo-range and the phase
observables. Their accuracy depends on the measuring accuracy,
the satellite configuration and the number of uncorrelated
observations used in the averaging process. For june 10th, 28
minutes, corresponding to 2800 observations are used whereas for
june 12th only 1400. For a differential solution the difference
between the cycle ambiguities computed at the stationary and
moving antenna are important.
An error in the differential values dA will result in a position
error. Due to the changing satellite geometry during the obser-
vation period this position error will not be constant but will
manifest itself as a drift in the position, like the results
shown in figure 6.

Introduction of the GPS positions in the photogrammetric adjust-
ment program (FOTEF).
Both a whole block and a single strip were calculated with seve-
ral combinations of ground control and GPS observations. The
block consists of the strips 3,4,5 and 6 from june 10th as men-
-tioned in table 1. In the calculations ground control points we-
re given a standard deviation of 5 cm in planimetry and 2 cm in
height. The GPS observations were given a standard deviation of
25 cm in planimetry and 100 cm in height (reflecting the found
offset in the height component). Model observations were given a
standard deviation of 10 microns in planimetry and 15 in height.
The results were compared with the "true" coordinates of the
complete set of ground control points as obtained from
terrestrial GPS observations and are shown in tables 3 and 4.
results for the block

GPS positions		no		yes	
		mean	rms	mean	rms
4 ground control points	X	.090	.121	.029	.105
	Y	.006	.068	.014	.041
	h	.016	.228	.028	.105
8 ground control points	X	-.024	.086	-.007	.074
	Y	.003	.047	-.001	.033
	h	-.015	.195	.011	.091

table 3: coordinate differences for the terrestrial
and photogrammetrically computed terrain
coordinates with standard deviations.

Since most maps at Rijkswaterstaat are produced at scale 1:1000,
coordinate precision better than 10 cm. in the terrain is accep-
table, translating to a precision of 0.1 mm on map scale. The
results in table 3 indicate that only four ground control points
do not fulfill our requirements completely. Using eight control

points and GPS-positions however, thus yield acceptable results.
The first column in table 3 shows the result of an adjustment
without GPS position coordinates using resp. four and eight
ground control points. The table shows that the introduction of
additional GPS observations is indeed necessary, since omitting
the latter results in a detoriation of the height precision and
a large offset in planimetry.
Normally about twenty ground control points in X,Y,Z and fifteen
additional height control points would be used. The results show
that a reduction of more than 50% in ground control is possible!

results for the strip

GPS positions		no		yes	
		mean	rms	mean	rms
4 ground control	X	-.367	.236	-.227	.148
points	Y	-.228	.214	-.046	.094
	h	-.096	.206	-.102	.197
6 ground control	X	-.041	.079	-.024	.057
points	Y	-.032	.078	-.027	.060
	h	.095	.162	.075	.147

table 4: coordinate differences for the terrestrial
and photogrammetrically computed terrain
coordinates with standard deviations.
(results for one strip)

Again we see, that the use of only four ground control points
plus GPS measurements does not yield satisfactory results. Ad-
ding two more ground control points already gives much better
rms values, although the offset in the height of 75mm is still
somewhat large.
The main problem is, that in a single strip the GPS observations
lie virtually on a straight line. This makes the determination
of the rotation along the flight axis a weak point. This ex-
plains that the addition of GPS measurements does not give a
dramatic improvement in the obtained precision. Therefore, until
the orientation angles of the airplane can be measured more
precisely (ref 3), for single strips additional photographs
should be taken alongside the strip to stabilize the solution.

6.Conclusions

The presented results show that relative position accuracies be-
tter than 10 cm can be obtained for kinematic GPS positioning
during a photo-flight.
Drifts with a magnitude of 0.2 - 0.4 mm/s are present in the re-
sults, probably due to the pseudo-range phase solution.
The overall attainable accuracies are sufficient to cope with

small and large scale mapping requirements.
For large scale applications a more refined photogrammetric- or
GPS-model solving for the coordinate offset and drift might give
even better results.
GPS flight navigation observations can in principle be included
in existing independent model triangulation software (not all
programs lend themselves for a smooth adaption).
Although the evaluation of the attainable reduction in ground
control is not yet fully completed, it is expected to be sub-
stantial when the GPS-observations are properly integrated in
the photogrammetric program. Future research should be focussed
on this integration of additional observations in the photogram-
metric adjustment model.

7. Discussion
For large scale mapping purposes it is necessary to correct for
the coordinate offsets and -drifts that are found in the
vertical components before the GPS positions are introduced as
observed projection-centre coordinates in a photogrammetric
adjustment program. This can be achieved by either introducing
extra parameters in the adjustment program itself to solve for
offset and drift or by applying a refined GPS solution.
A practical solution might be to determine the GPS projection-
centre coordinates of one photograph from at least three
targetted ground control points known in GPS coordinates and
visible in this photograph. This projection-centre than acts as
a known starting point relative to which all other GPS positions
can be determined from integrated phase measurements only.
At present the results of this solution are not yet available.

8. References

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